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High-power microwaves response characteristics of silicon and GaAs solar cells

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Abstract: The high-power microwave (HPM) effect heats solar cells, which is an important component of a satellite. This creates a serious reliability problem and affects the normal operation of a satellite. In this paper, the different HPM response characteristics of two kinds of solar cells are comparatively researched by simulation. The results show that there are similarities and differences in hot spot distribution and damage mechanisms between both kinds of solar cell, which are related to the amplitude of HPM. In addition, the duty cycle of repetition frequency contributes more to the temperature accumulation of the solar cells than the carrier frequency. These results will help future research of damage assessment technology, reliability enhancement and the selection of materials for solar cells.

Key words: solar cells; silicon; GaAs; HPM; repetition frequency; response characteristics

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1. Introduction

Currently, increasing numbers of satellites are launched to perform a wide variety of tasks, such as navigation and positioning, meteorological observation and prediction, geological exploration and so on. However, these tasks consume a lot of energy, which comes from the power system. As the key component of most satellite energy systems, solar cells charge the batteries when lit and provide power for the whole system when located in a shadow area[1−3]. Therefore, as an important part of a satellite's power supply system, solar cells are vital to the normal operation of a satellite and their reliability is among the issues of common concern[4, 5].

As one of the electromagnetic pulses, high-power microwaves (HPMs) can enter electronic equipment through the "front door" coupling or "back door" coupling, and then generate electric and thermal effects inside the components of the electronic system, thus affecting the normal operation of the electronic system or even causing it to fail[6−9]. Usually, the medium coupled by the front door includes the transmission line and antenna of the satellite, while the exposed cathode in solar cells can be regarded as an antenna. Thus, the HPM can be coupled into the interior through the thin cathode wires and generate high-amplitude current pulses, which will affect the normal operation of electronic components, and can even impact the electronic systems of spacecraft such as satellites, thus affecting the reliability and life of spacecraft[10−12]. Therefore, it is very important to study the HPM response characteristics of solar cells.

Among solar cells, silicon solar cells, high efficiency GaAs solar cells, multi-junction solar cells or their combination are applied to satellites[13, 14]. Among them, silicon solar cells were first used in satellites due to mature preparation technology, low price and other factors[15−17]. GaAs solar cells occupy a place in satellite solar cells due to their high photoelectric conversion rate, good radiation resistance and high-temperature resistance[18−20]. At present, there are few studies on the HPM response characteristics of two kinds of solar cells and they all focus on GaAs solar cells.

In 2020, Xue *et al.*[21] used CST microwave studio to study the electric coupling effect of HPM of monolithic GaAs solar cells and found that high-power electromagnetic pulse produced transient strong electric field and high-voltage effect on solar cells, and mainly concentrated in the edge of solar cells. In 2021, Wang *et al.*[22] studied the HPM damage effect of GaAs solar cells and found that the damage mechanism of GaAs solar cells was related to the frequency of injecting signal.

In this paper, based on the two-dimensional thermoelectric model established by Sentaurus-TCAD software, the hot spot distributions and corresponding damage mechanism of silicon and GaAs solar cells under HPM with different amplitudes are comparatively researched and analyzed. In addition, the influence of repetition frequency, which is an important part of HPM, on two kinds of solar cells has also analyzed. This research may form a certain reference for future research on location prediction technology and the reliability enhancement of solar cells, and provide suggestions for their application protection and the selection of materials of solar cells.

2. Structures and models

According to the equivalent device model cut from the multi-junction silicon solar cells and the GaInP/GaAs/Ge triple-junction solar cells[23, 24], the two-dimensional structure models of their single-junction are constructed; as depicted in Figs. 1(a) and 1(b). For the convenience of comparative analysis, the length and total thickness of the two models are consistent; the details of thickness are shown in Table 1.

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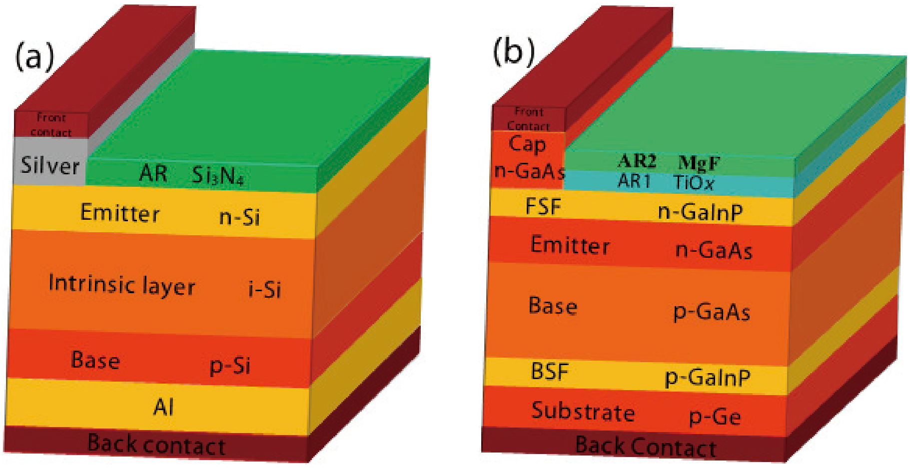

Fig. 1. (Color online) (a) Three-dimensional view of a single junction silicon solar cell. (b) Three-dimensional view of a single junction GaAs solar cell.

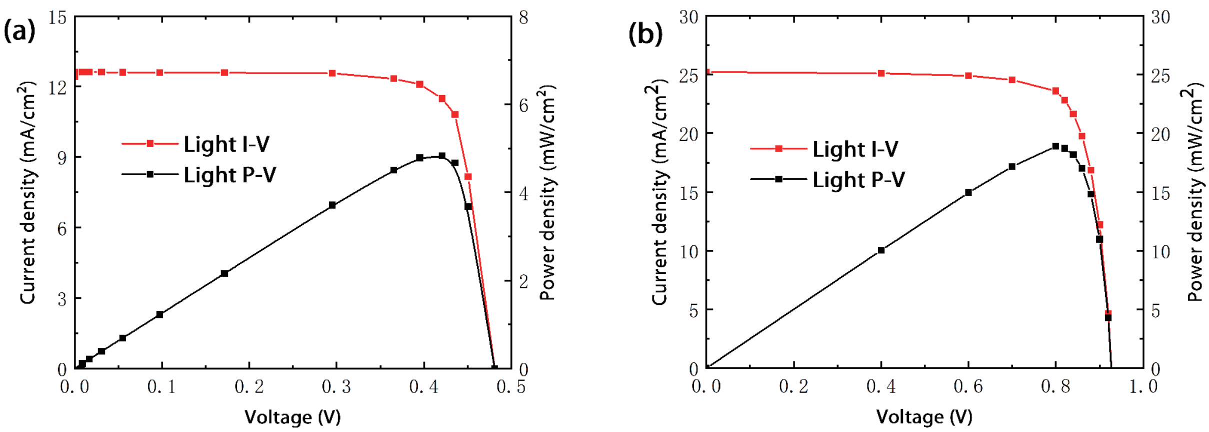

Fig. 2. (Color online) (a) The light *I*–*V* and *P*–*V* characteristic curves of silicon solar cells. (b) The light *I*–*V* and *P*–*V* characteristic curves of GaAs solar cells.

Table 1. The details of the thickness (μm) of two kinds of solar cells.

Silicon solar cell		GaAs solar cell	
Silver	0.3	Cap	1
Emitter	0.2	FSF	0.03
Intrinsic layer	2.3	Emitter	0.1
Base	0.18	Base	1.5
Al	0.1	BSF	0.05

In this figure, the emitter region is an n-type doped region and most carriers are electrons. The base region is a p-type doped region, and the most carriers are holes. Under the action of photogenerated electromotive force, electrons in the N region pass through the PN junction and enter the P region. This phenomenon is similar to the principle of bipolar transistors. Thus in the solar cells, the area where electrons leave is called the emitter, and the area where electrons receive is called the base. Besides, BSF is the abbreviation of back surface field, which is used to reduce reflection and increase the conversion efficiency of solar cells. AR is an antireflection film, which can reduce the reflection of incident light on the surface of solar cell, increase more light absorption and improve its photoelectric conversion efficiency.

Higher electric field intensity and current density are generated in the device after injecting the HPM signal. In this paper, in addition to the common avalanche multiplication and thermodynamic model used[25] to simulate the carrier transport in solar cells, the influence of self-heating effect on the internal temperature diffusion of solar cells needs to be considered. The specific equation is shown as follows:

$$c\frac{\partial T}{\partial t}-\nabla\cdot k\nabla T=-\nabla\left[\left(P_{\rm n}T+\phi_{\rm n}\right)J_{\rm n}+\left(P_{\rm p}T+\phi_{\rm p}\right)J_{\rm p}\right] -\left(E_{\rm c}+\frac{3}{2}k_{\rm B}T\right)\nabla\cdot J_{\rm n}-\left(E_{\rm v}-\frac{3}{2}k_{\rm B}T\right)\nabla\cdot J + qR\left(E_{\rm c}-E_{\rm v}+3k_{\rm B}T\right), \quad (1)$$

where $\phi_{\rm p}$ ($\phi_{\rm n}$) is the hole (electron) quasi-Fermi potential, $P_{\rm p}$ ($P_{\rm n}$) is the hole (electron) absolute thermoelectric power, c is lattice heat capacity, k is thermal conductivity and R is recombination rate.

3. Results and discussion

Under AM0 solar spectrum (P = 136.7 mW/cm^2, T = 300 K), the *I*–*V* and *P*–*V* curves of silicon and GaAs solar cell are presented in Figs. 2(a) and 2(b).

In solar cells, short-circuit current density ($J_{\rm sc}$) and open-circuit voltage ($V_{\rm oc}$) are directly proportional to photovoltaic current ($J_{\rm ph}$), and the specific relationships are shown as follows:

$$J_{\rm sc}=J_{\rm ph}, \quad (2)$$

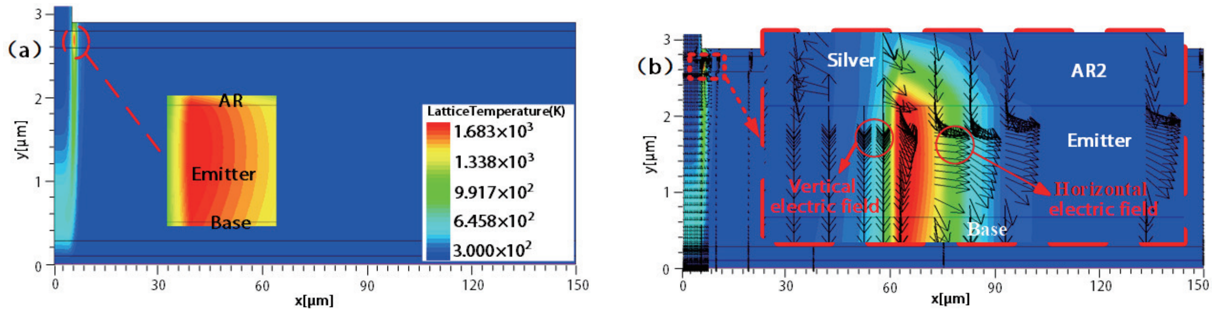

Fig. 3. (Color online) A silicon solar cell when it is burned out under injecting HPM with an amplitude of 270 V and frequency of 2 GHz. (a) Temperature distribution in the device. (b) The trend distribution of electric field intensity near the hot spot in the device.

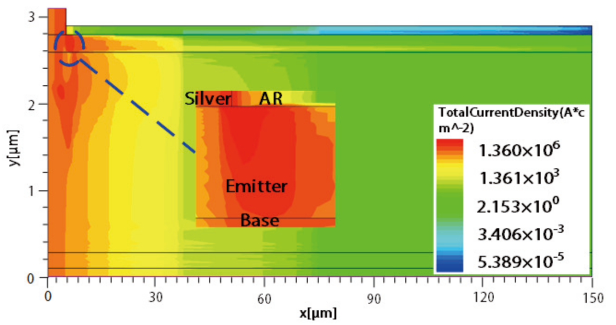

Fig. 4. (Color online) The variation of HPM sinusoidal signal with time and the variation of peak temperature of Silicon solar cells under injecting this signal with time.

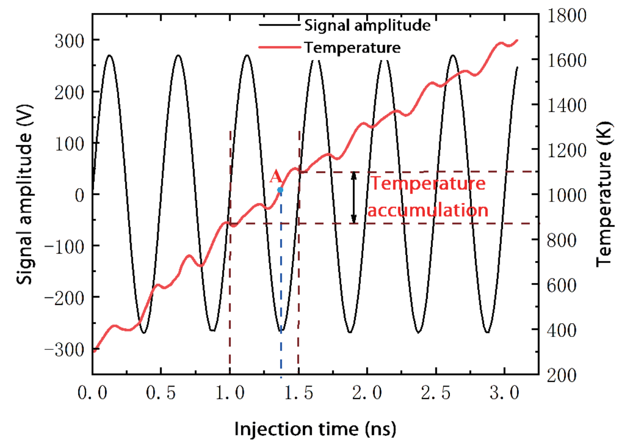

Fig. 5. (Color online) The variation of HPM sinusoidal signal with time and the variation of peak temperature of the silicon solar cell under injecting this signal with time.

$$V_{oc} = \frac{k_0 T}{q} \ln\left(\frac{J_{ph}}{J_s} + 1\right). \tag{3}$$

The J_{sc} and V_{oc} of GaAs solar cell are larger than those of silicon solar cells in Fig. 2; that is, its J_{ph} is larger than that of silicon solar cell, which is consistent with the known conclusion[26, 27].

Considering the comparison with anode metal plate of a solar cell, the thin wire of cathode metal cap is easy to be coupled by HPM, and the HPM can even be injected back through the coupling power line. Consequently, in the simulation, the equivalent sinusoidal signal of HPM shown in Eq. (4) is injected into the cathode port of solar cells.

$$U = U_0 \sin(2\pi ft + \varphi). \tag{4}$$

where U_0 is the maximum injection amplitude, f is the injection frequency and φ refers to the initial phase. Silicon solar cells and GaAs solar cells are burnt out at their materials melting points of their materials[28]; that is, 1683 and 1511 K respectively.

3.1. Damage mechanism of silicon solar cells

In a silicon solar cell, the emitter region and base region form a PN junction and a space charge region is formed at the interface. Due to the action of built-in electric field in the space charge region, the vertical photo-generated electromotive force is formed, and the direction is from P region to N region; that is, from bottom to top. After injecting HPM, due to the difference in length between the cathode thin line and the anode plate, in addition to the vertical electric field, a horizontal electric field is formed. The horizontal electric field and the vertical electric field work together, and finally a hot spot near the cathode thin line is formed in silicon solar cell; as shown in Fig. 3(a). The electric field direction at the hot spot of the solar cell is analyzed, and the Fig. 3(b) is obtained. Among them, the horizontal electric field and vertical electric field are clearly displayed in the form of arrows. The denser the arrow distributions, the greater the electric field strength.

The burnout mechanism of the hot spot is further explored and it is found that the current density is the highest shown in Fig. 4. The higher the current density at the hot spot, the more Joule heat is generated. Due to the limited device size and short action time, the generated Joule heat cannot spread out and act on the hot spot. When the amplitude of the negative half-cycle of the injected signal is the maximum, the temperature rise of the silicon solar cell reaches the maximum (point A) seen from Fig. 5, which contributes the most to the temperature accumulation. Due to the larger current of PN junction in forward bias, the Joule heat accumulation effect is more obvious and the contribution to its temperature rise is greater. With the increase of injection time, the temperature at the hot spot gradually accumulates until it reaches 1683 K.

3.2. Damage mechanism of GaAs solar cells

After the injection of HPM, it is found that besides the hot spot similar to the silicon solar cell, a hot spot near the back surface field of the anode in the base region in the GaAs solar cell is shown in Fig. 6(a). By further exploring the hot spot in the base region, it is found that the electric field intensity at this location is the largest shown in Fig. 6(b). When elec-

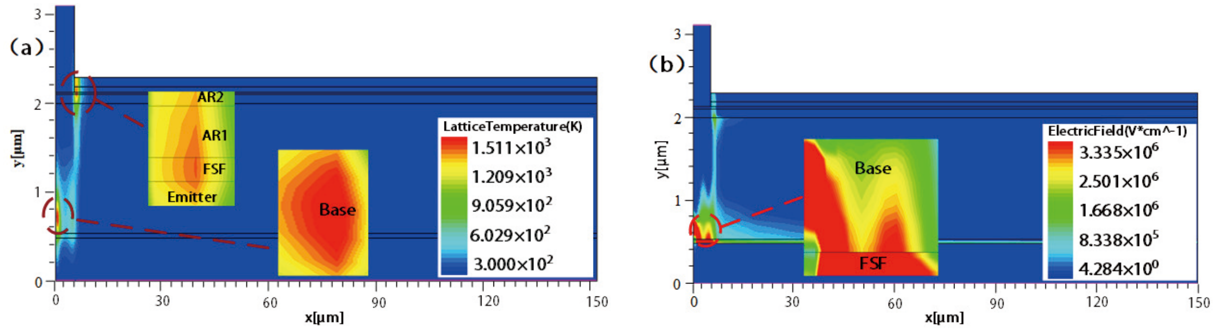

Fig. 6. (Color online) The GaAs solar cell when it is burned out under injecting HPM with an amplitude of 270 V and frequency of 2 GHz. (a) Temperature distribution in the device. (b) The electric field intensity distribution of the device.

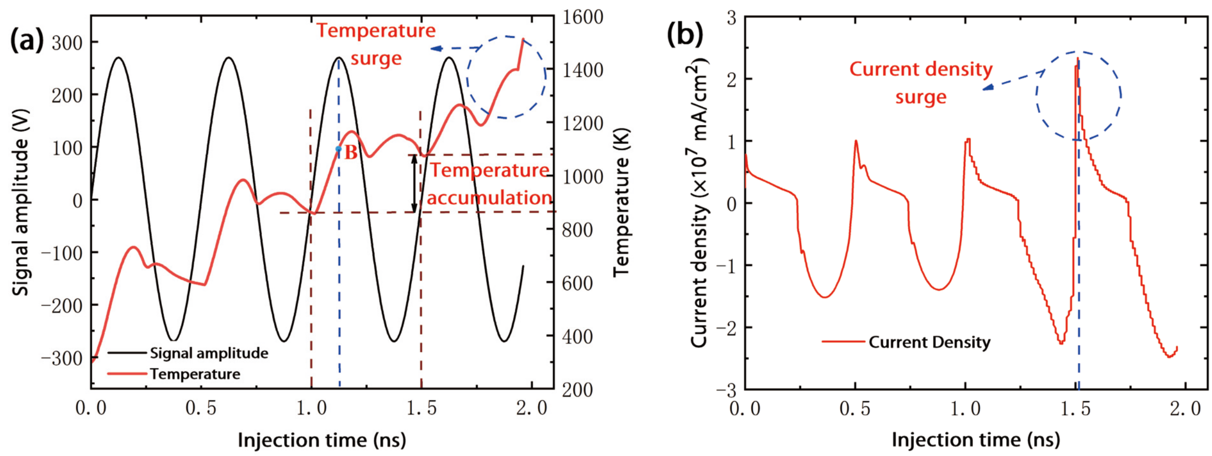

Fig. 7. (Color online) Under the injection of HPM with an amplitude of 270 V and frequency of 2 GHz. (a) The variation of HPM sinusoidal signal with time and the variation of peak temperature of the device with time. (b) The variation of current density with time in the device.

trons or holes pass through the space charge region, the stronger the electric field strength, the more their energy increases, the easier it is to reach a certain level and collide with electrons in the atoms in the depletion region, thus generating new electron–hole pairs, and the easier it is to have avalanche multiplication effect. Carriers are easy to accelerate in a wide barrier region to reach the kinetic energy of avalanche multiplication effect, so avalanche multiplication effect is more likely to occur in the base region of the GaAs solar cell in the positive half cycle of the applied signal, that is, when the PN junction is reversed.

When the amplitude of the positive half-cycle of the injected signal is the maximum, the temperature rise of the GaAs solar cell reaches the maximum (point B) seen from Fig. 7(a), which contributes the most to the temperature accumulation. As seen from Fig. 7(b), the current density of the GaAs solar cell increases sharply at the injection time of around 1.52 ns and, at this moment, the avalanche multiplication effect is the main burnout mechanism. In contrast to Joule heat, avalanche multiplication effect has a shorter action time and a more obvious current surge. With the increase of injection time, under the combined action of Joule heat and avalanche multiplication effect, the temperature at the hot spot of the GaAs solar cell gradually accumulates and soars at around 1.78 ns, resulting in its burnout.

3.3. The influence of the amplitude of HPM on the damage of solar cells

The variation of the burnout pulse width of silicon and GaAs solar cells under HPM injection with the same frequency but different amplitude is shown in Fig. 8. The relationship can be fitted into the following formulas, respectively[29]:

$$U_{\mathrm{Si}} = 563.116\tau^{-0.661}, \tag{5}$$

$$U_{\mathrm{GaAs}} = 328.099\tau^{-0.348}, \tag{6}$$

where U is the voltage amplitude of injected HPM, τ is the burnout pulse width. According to the fitting situation, the correlation coefficients of Eqs. (5) and (6) are both between 0.95 and 1, which shows a high fit. Let $U_{\mathrm{Si}} = U_{\mathrm{GaAs}}$, and get the signal amplitude of 179.94 V.

When $U_0 > 179.94$ V, the main burnout mechanisms of the two kinds of solar cells are different. Compared Fig. 5 with Fig. 7, it is found that the temperature accumulations of the two solar cells are almost similar. However, after being injected HPM for a period of time, the carriers in the GaAs solar cell reach the kinetic energy needed for avalanche multiplication, thus the avalanche multiplication effect occurs in the base and the surges in current density appear, which contributes more to the temperature rise than Joule heat accumulation.

When $U_0 < 179.94$ V, Joule heat accumulation is the main burnout mechanism of two solar cells. The forbidden bandwidth of silicon is narrower than that of GaAs, thus intrinsic excitation is more likely to occur. Although the burnout point of silicon solar cells is higher than that of GaAs solar cells, the generated current density is larger under injecting HPM

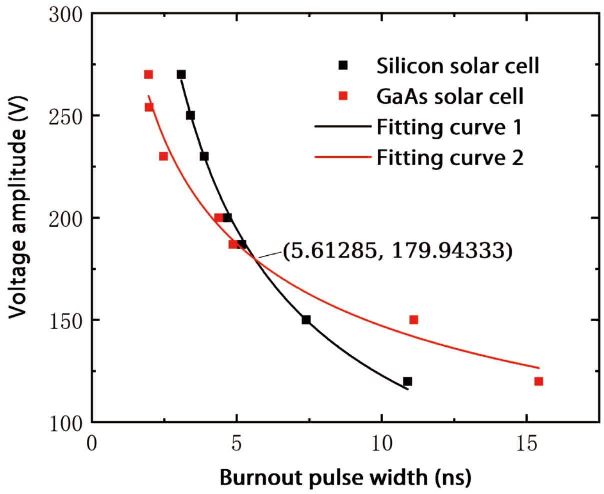

Fig. 8. (Color online) Actual variation and fitting variation of the burnout pulse width of the two kinds of solar cells with the voltage amplitude of HPM.

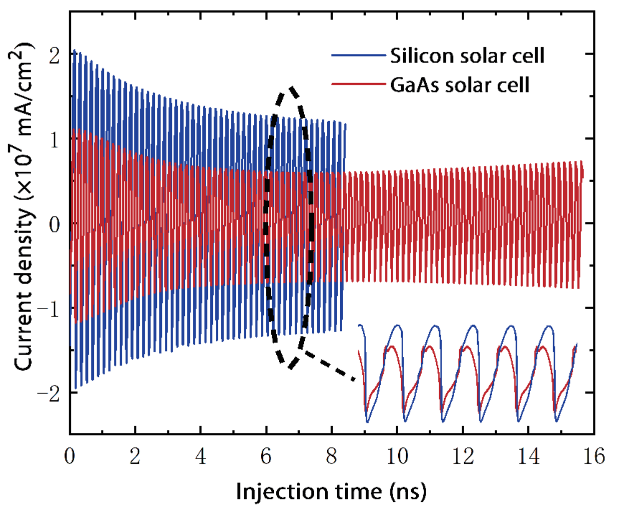

Fig. 9. (Color online) The variation of current density in the two kinds of solar cells under injecting HPM with an amplitude of 120 V and frequency of 5.8 GHz with time.

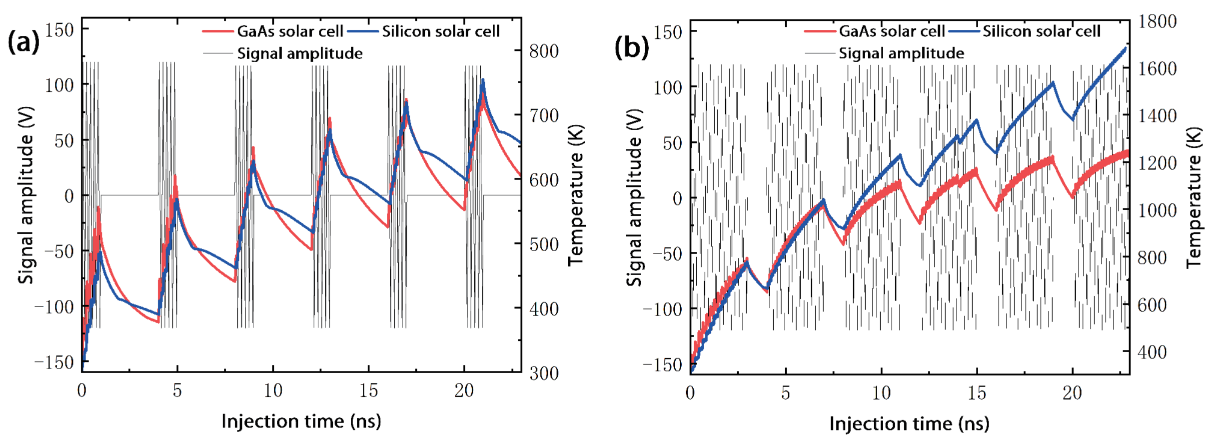

Fig. 10. (Color online) Variation of repetition frequency with different duty ratio with the injection time, variation of temperature of the two solar cells with time after injecting the signal. (a) Repetition frequency with duty ratio of 25%. (b) Repetition frequency with duty ratio of 75%.

(Fig. 9), which contributes more to Joule heat and is easier to reach the melting point to be burned out.

3.4. The influence of repetition frequency on burnout of two kinds of solar cells

Repetition frequency is a significant form of HPM and one of the main factors that cause device damage[30, 31]. This paper mainly discusses the influence of repetition frequency on the burnout of two kinds of solar cells from two factors of duty ratio and carrier frequency.

After injecting repetition frequency with an amplitude of 120 V, repetition frequency of 250 MHz, carrier frequency of 5 GHz and the duty ratio of 25% and 75%, respectively, it is found that the repetition frequency with high duty ratio contributes greatly to the burnout of two kinds of solar cells (Fig. 10). The higher the duty ratio of the repetition frequency, the clearer the difference of temperature rise between them. Especially when the temperature reaches 1000 K, the temperature rise of silicon solar cells is much higher than that of GaAs solar cells, which is related to the greater contribution of silicon solar cells to Joule heat in Section 3.3.

After injecting repetition frequency with an amplitude of 120 V, repetition frequency of 250 MHz, duty ratio is 50%, and the carrier frequency is 2 and 5 GHz respectively, it is found that the repetition rate of the high carrier frequency contributes more to the burnout of both solar cells (Fig. 11), but the effect on the temperature rise is smaller than the duty cycle. Between the two long injecting pulses, the local temperature of silicon solar cells decreases more slowly than that of GaAs solar cells, so the temperature accumulation is more obvious and contributes more to the burnout.

4. Conclusion

In this paper, two-dimensional thermoelectric models of two kinds of solar cells are established and the HPM response characteristics of both are explored. By analyzing simulation results, it is concluded that there is a hot spot in silicon solar cells, which is finally burned out near the cathode due to Joule heat accumulation, and the negative half cycle of the signal contributes the most to the burnout. Meanwhile, GaAs solar cells have two hot spots, one is similar to silicon solar cells, the other is near the back surface field of the anode, are finally burned out due to avalanche breakdown, and the burnout pulse width is smaller than that of silicon solar cells. When the frequency of HPM is constant, the amplitude decreases below 179.94 V, the hot spot of GaAs solar cells

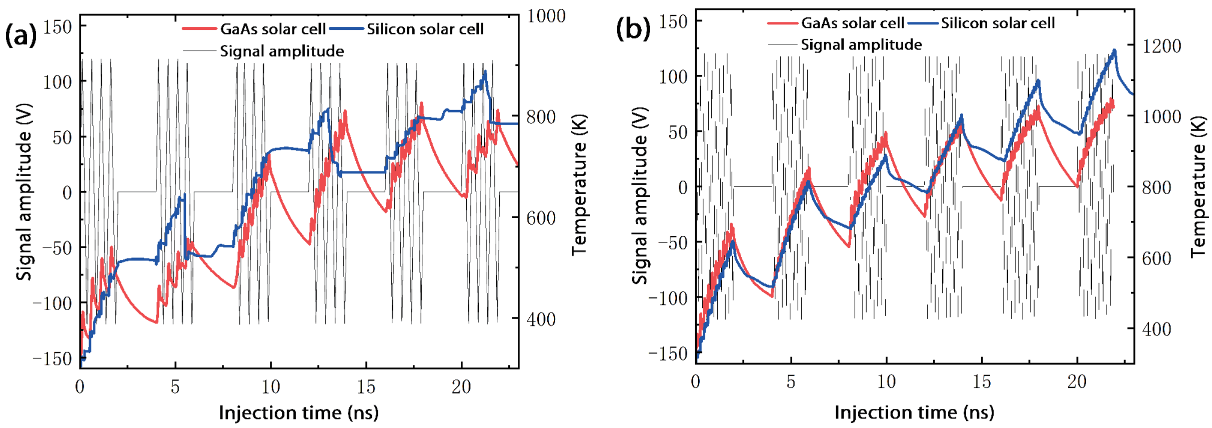

Fig. 11. (Color online) Variation of repetition frequency with different carrier frequency with the injection time, variation of temperature of the two solar cells with time after injecting the signal. (a) Repetition frequency with carrier frequency of 2 GHz. (b) Repetition frequency with carrier frequency of 5 GHz.

transfers, and the chief burnout mechanism changes from avalanche breakdown to Joule heat accumulation. At this time, because the forbidden bandwidth of Si is narrower than that of GaAs, intrinsic excitation is more likely to occur. Under the injection of the same HPM, the current density in silicon solar cells is higher, and its burnout pulse width is smaller than that of GaAs solar cells. In addition, by injecting the repetition frequency with different duty ratio or carrier frequency, it is found that when compared with the carrier frequency, the repetition frequency with a high duty ratio contributes more to the burnout of two kinds of solar cells, especially after the temperature reaches 1000 K, the silicon solar cells are more likely to be burned out.

Acknowledgements

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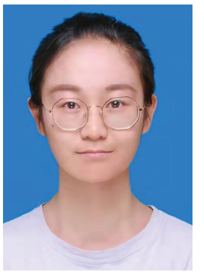

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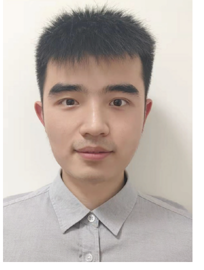

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